FIRST ASSESSMENT OF GPS-BASED REDUCED DYNAMIC ORBIT DETERMINATION ON TOPEX/POSEIDON

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Abstract. The reduced dynamic tracking technique has been applied for the first time as part of the GPS experiment on TOPEX/Poseidon. This technique employs local geometric position corrections to reduce orbit errors caused by the mismodeling of satellite forces, at the expense of an increase in random error. Results for a 29-day interval in early 1993 are evaluated through postfit residuals and formal errors, comparison with GPS and DORIS dynamic solutions, orbit comparisons on 6-hr overlaps of adjacent 30-hr data arcs, altimetry closure and crossover analysis. Reduced dynamic orbits yield slightly better crossover agreement than other techniques and appear to be accurate in altitude to 3 cm.

Introduction

The GPS experiment on TOPEX/Poseidon (Melbourne et al., 1993) presents the first opportunity to apply the reduced dynamic technique for precise orbit determination of earth satellites (Wu et al., 1991; Yunck et al., 1990). The technique exploits the great observing strength of GPS to make local geometric corrections to the satellite orbit obtained in a conventional dynamic solution. This reduces orbit errors arising from the mismodeling of forces acting on the satellite, while increasing somewhat the effects of measurement error. The principle is illustrated in Fig. 1. The solid line represents a dynamic orbit solution in which the solution trajectory is described by a set of physical and empirical force models, which may have been adjusted in the solution, The dashed line represents the observed orbit embodied in the GPS data. The dynamic orbit solution yields a set of postfit data residuals reflecting the difference between the solution orbit and the measurements. The size of that difference depends in part on the accuracy of the force models used in the dynamic solution. Because the flight receiver typically tracks five or six GPS satellites at

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once, at each time step there is sufficient residual information to construct geometrically the 3D vector between the dynamic solution and the observed orbit. Thus the observed orbit can be fully recovered to replace the model orbit as the orbit solution,

'I'his concept offers a continuum of possible solution strategies. At one extreme we can give no weight to the geometric corrections and retain the dynamic solution. At the other extreme we can fully apply the geometric corrections to obtain a kinematic solution, In that case the underlying dynamic solution serves as a point of departure but has little influence on the geometrically determined orbit, and the effects of force model errors are greatly reduced. In between we can give arbitrary relative weight to dynamic and geometric information by constraining the geometric correction with respect to both the dynamic solution and the previous correction, partially reducing dynamic model error. An "optimal" weighting will tend to balance dynamic, geometric, and measurement errors.

Solution Strategy

The results presented here were obtained with JPL's GIPSY/OASIS 11 analysis software (Wu and Thornton, 1985). Briefly, the software is structured as a sequential Kalman filter which processes undifferenced GPS data collected concurrently from the flight receiver and a set of ground receivers. For this analysis, 13 ground sites have been used. Data arc lengths of 30 hrs were chosen, with consecutive arcs containing a 6-hr common overlap to permit direct orbit comparisons. The TOPEX/Poseidon orbit solution is obtained as part of a simultaneous solution for many parameters, including GPS orbits; 8 ground site positions (5 are held fixed for reference); receiver and transmitter clock offsets at all but one site, adjusted independently at each time step (white noise clock model); all carrier phase biases; zenith tropospheric delays at each site, adjusted every 5 min as a random walk process; and several empirical forces on TOPEX/Poseidon and the GPS satellites.

The TOPEX/Poseidon solution must be iterated to convergence. The dynamic solutions, which adjust once- and twice-per-rev and constant empirical force parameters to accommodate unmodeled accelerations, converge in two iterations. The reduced dynamic solutions begin with a converged dynamic solution, hold the empirical parameters fixed, and perform a final iteration to estimate the local corrections. As those corrections arc small, no further iteration is needed, Table 1 summarizes the general solution strategy.

Results

After several months of experimentation with early data, we have focused on a 29-day interval beginning on 1 Mar 1993. This encompasses three complete 10-day repeat cycles. Reduced dynamic solutions are assessed with several measures, including RMS postfit phase residuals, formal errors, comparison with GPS dynamic solutions, comparison with dynamic solutions obtained with Doppler data from the French DORIS system, 6-hr overlap agreement of adjacent solutions, and altimetry closure and crossover agreement,

Postfit Residuals. The precision of the dual frequency carrier phase observable from the flight receiver is expected to be 4-5 mm, with multipath and receiver thermal noise the dominant errors. If the observing geometry and satellite dynamics were modeled perfectly, the postfit phase residuals at each receiver would be at the level of the measurement precision. But owing to force model errors, the TOPEX/Poseidon model trajectory is imperfect, and dynamic residuals are higher for flight data. The actual dual frequency RMS residuals for TOPEX/Poseidon, averaged for all 29 days, were 1.2 cm for dynamic, and 4.8 mm, or about the level of the measurement noise, for reduced dynamic. (Ground residuals are about 4.5 mm in both cases.) This does not imply that reduced dynamic is the superior solution—further tests are needed for that. But residuals at the noise level are expected if the reduced dynamic solution is working properly.

Formal Errors. Formal errors computed by the filter for the orbit solution are based solely on the data weights and a priori errors assigned by the analyst. The assigned weights represent l-sigma values for independent random noise. For the dynamic solution, where the total error is dominated by systematic model errors, the formal error will be optimistic unless a conservative data weight is used. For the reduced dynamic solution, the total error is dominated by measurement error, and weights reflecting true measurement error should yield a reliable formal error. A weight of 1 cm was assigned to phase (both flight and ground) in the reduced dynamic solutions, or double the actual postfit RMS residuals, The forma] error, shown for a typical solution in Fig. 2, is below 2 cm for altitude, with a chi-squared value of 0.25. In reality, subtle systematic errors may be absorbed in the grand solution, and add several centimeters to the total error,

Dynamic v. Reduced Dynamic. In early studies employing the JGM-1 gravity model (the best available at the time of launch) the RMS altitude difference between dynamic and reduced dynamic solutions was 6-7 cm. We later adopted the JGM-2 model, which was tuned with TOPEX/Poseidon laser and Doppler data at the Goddard Space Flight Center (Lerch et al., 1993). The new dynamic solution has moved closer to reduced dynamic, with an average RMS altitude difference of 3.4 cm. Figure 3 plots the three component differences for a typical 30-hr arc. The smooth character of the curves and the evident once-per-rev signature suggest that the reduced dynamic solution is primarily correcting dynamic model error rather than introducing measurement error.

Comparisons with DORIS and lasers. We have estimated TOPEX/Poseidon orbits with one-way Doppler data from the French DORIS system (Cazenave et al., 1992), which along with laser ranging provides operational precise tracking for the satellite. DORIS is an uplink-only system with more than 40 transmitters around the world. Estimated parameters include the satellite state, a constant along-track acceleration, along-track and cross-track once/rev accelerations, zenith tropospheric delays and clock rates at each transmitting site for each pass. Figure 4 shows the typical agreement between GPS reduced dynamic and DORIS solutions over 30 hrs. Similar results have been obtained by others (e.g., Schutz et al., 1993). In a blind comparison, dynamic solut ions obtained at the Goddard Space Flight Center with DORIS and laser data (and a tuned drag model) showed an RMS altitude agreement of 3.4 cm with the GPS reduced dynamic solution over 20 days, (S, Nerem, GSFC, private communication)

Overlap Agreement. The daily 30-hr data arcs provide a 6-hr common overlap for orbit comparison. Figure 5 shows the RMS altitude agreement over the central 4.5 hrs of the 28 overlaps for the 29 reduced dynamic solutions. The average RMS agreement is 0.9 cm. Since the data are identical on the overlaps and the solution is partly geometric (i.e., local), one might ask what causes the discrepancy. Note that the GPS satellite orbits are computed dynamically over each 30-hr arc and will therefore disagree on the overlaps, since their solutions are substantially influenced by non-common data. That discrepancy will then appear (reduced by about 20:1) in the TOPEX/Poseidon geometric corrections. We can see in Fig. 5 that the overlap agreement improves over the 30 days. It happens that during the first 10 days, up to 7 of the 22 GPS satellites were passing through the earth's shadow on each orbit. By the last 9 days, *no* GPS satellites were eclipsing, It has long been known that eclipsing orbits are more difficult to model. The average 3D RMS overlap agreement for the 22 GPS satellite orbits falls from about 29 cm for the first 9 days to less than 19 cm for the last 9 days, which largely explains the improving TOPEX/Poseidon overlaps,

Laser Heights and Altimetry Closure. The TOPEX/Poseidon Project has set up two verification sites, on the Harvest oil platform off the California coast and on an island in the Mediterranean. The sites are equipped with tide gauges and GPS receivers, and are almost directly overflown by TOPEX/Poseidon every 10 days. The satellite altitude over the sites was measured with short (10 min) arcs of laser ranging data collected nearby, thereby eliminating dynamic model error (Bonnefond et al., 1993). Laser height estimates for 7 Harvest overflights were compared with dynamic and reduced dynamic GPS (Fig. 6). While the dynamic solutions agreed somewhat better in the mean, both agreed within the expected laser error. The reduced dynamic agreement was more consistent, with a standard deviation of 1.5 cm compared with 2.4 cm for dynamic. In a second test, orbit height, tide gauge and GPS ground survey data were combined to give independent estimates of the altimeter range for calibrating the altimeter bias. All orbit solutions—laser, DORIS, and GPS—produced bias estimates of 17-19 cm, but again the reduced dynamic estimates showed the least variation. For more details see Christensen et al., this issue.

Crossover Analysis. In theory, we can test how reliably ocean height is obtained from the estimated orbit altitude minus the altimeter measurement by comparing ocean height measurements at orbit crossover points. As crossovers may occur days apart, corrections for surface variation, such as ocean and solid tides, must be applied. A confounding factor is the unmodeled sea height variation from changes in ocean currents and tide model errors. As that variation can be large (10 cm or more) compared with expected orbit accuracy, such a test is in practice less than ideal, but still useful for comparing orbits. We have identified two ocean regions where the current variation over short periods is relatively low (Fig. 7), and computed crossover agreements in both regions, as well as globally, for GPS reduced dynamic orbits and the GSFC laser/DORIS orbits. GPS yields consistently better agreement, but by small amounts since orbit error is largely masked by ocean variation. If we assume a global "noise floor" of 9-10 cm from the ocean then the 4.5 mm reduction in global RMS crossover residuals suggests an improvement in orbit repeatability of 2-3 cm for the reduced dynamic orbits.

Degraded Dynamics. To better test the strength of reduced dynamic tracking, we have computed orbit solutions with the older GEM-T1 gravity model (Marsh et al., 1988) in place of the tuned JGM-2 model. Figure 8 shows the difference between a dynamic solution with GEM-T1 and the reduced dynamic solution with JGM-2 for a single day. Effectively all of the difference, which includes excursions of 77 cm in altitude and 1.6 m 31), results from the error in GEM-T1. This is about the level of model error we might face from both gravity and atmospheric drag at altitudes of 700-800 km. Figure 9 shows the difference between reduced dynamic solutions with the two gravity models. The GEM-T 1 reduced dynamic solution has recovered much of the JGM-2 information in one step. We expect that tuning of the strategy for poor dynamics will improve this agreement further.

Discussion and Conclusions

Dynamic and reduced dynamic orbit solutions in principle have quite different limiting errors, Random measurement error is small in the dynamic solution, which is limited by the mismodeling of gravity, solar pressure, thermal radiation, and other forces. Properly constrained, the reduced dynamic solution will track the motion caused by those forces and instead be limited by measurement and geometrical modeling error. The difference between the two may therefore give a fair upper bound on the true error for each. The evidence at this point does not conclusively favor either approach, although the closure and crossover statistics, which are independent tests of orbit quality, point to reduced dynamic as the more consistent solution. Formal errors for the reduced dynamic solutions are below 2 cm, but subtle systematic errors may boost the true error higher. We believe the evidence supports an estimate of 3 cm RMS for the reduced dynamic altitude error.

The GPS experiment on TOPEX/Poseidon is still a work in progress. Many small improvements will be made in the next year, including refined gravity and dynamic tide models, models of ocean and atmospheric loading, calibration of transmit antenna phase variations and receiver systematic errors, better models of the GPS satellite “noon turn” and dynamics during eclipsing, an upgraded onboard satellite selection algorithm, site- and elevation-dependent data weighting, and an attempt to resolve satellite-to-ground cycle ambiguities. Orbit accuracy may yet be improved by another factor of two.

Both dynamic and reduced dynamic orbit solutions appear to be accurate to better than 10 cm RMS. The efforts in recent years to refine TOPEX/Poseidon force models have paid off, and the mission can therefore benefit only modestly from the lower force model sensitivity reduced dynamic tracking offers. Altimetric satellites now being planned for lower altitudes will face a more complex dynamic environment, and dynamic solutions of the present quality will be difficult and costly to attain, Reduced dynamic tracking, with its essential reliance on geometry, should degrade very little and may offer the only practical means of reaching few-centimeter orbit accuracy at low altitudes,

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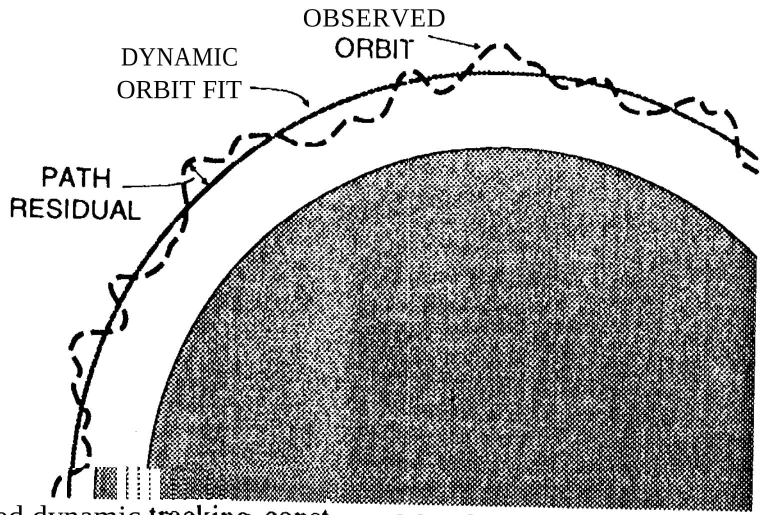

Fig. 1. In reduced dynamic tracking, constrained local geometric corrections are applied to an initial dynamic orbit solution.

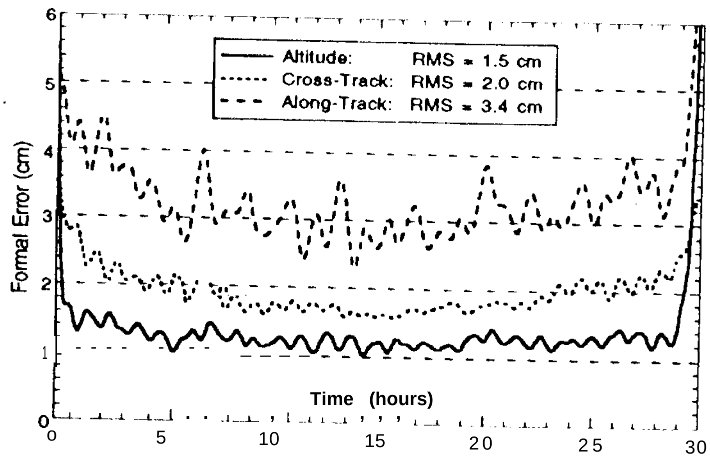

Fig. 2. Typical formal errors for reduced dynamic TOPEX/Poseidon orbit solution. Absence of data outside interval causes edge effects.

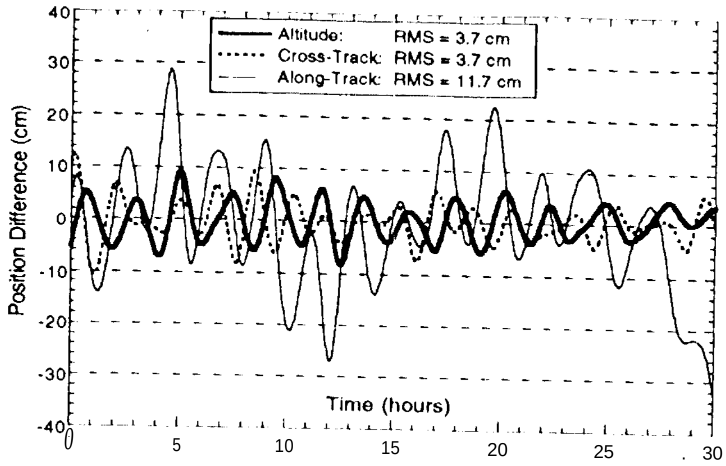

Fig. 3. Difference between dynamic and reduced dynamic orbits for typical solutions. Altitude excursions are less than 10 cm.

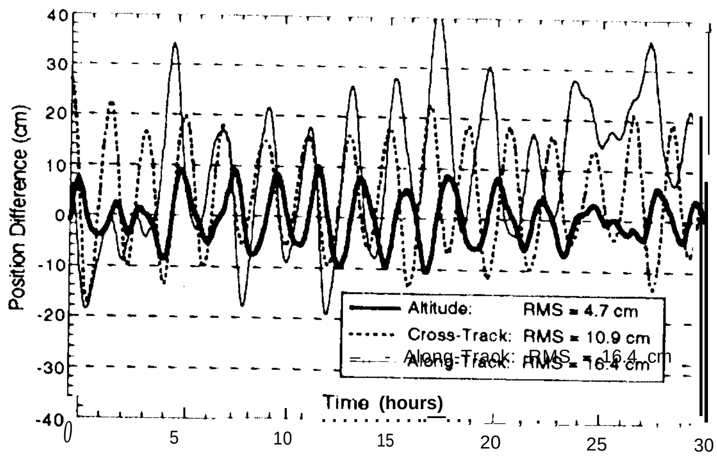

Fig. *4*. Differ-wee between GPS reduced dynamic and DORIS dynamic orbits for typical solutions.

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TABLE 1. Summary of TOPEX/Poseidon Orbit Determination Strategy

System Description	
Orbit (circular):	1336 km, 63° inclination
Number of Ground Sites:	13 (5 held fixed)
Number of GPS Satellites:	20-22
Flight Antenna Field of View:	hemispherical
Flight Receiver Tracking Capacity:	6 satellites (L1 and 1.2)
Data Types:	pseudorange and carrier phase
Data Intervals:	S-rein batches, 30-hr data arcs
Data Weights:	1 cm, phase; 1 m, pseudorange
Earth Gravity Model:	JGM-2
Adjusted Parameters and A Priori Errors	
TOPEX/Poseidon State:	1 km; 1 m/sec, each component
GPS Satellite States:	I km; 1 rn/see, each component
In-Track, Cross-Track Const. Accel:	10^6 nm/s^2, each component
2D Once/Twice per Rev Accel:	10^6 nm/s^2, each component
Carrier Phase Biases:	30,000 km
GPS and Receiver Clock Biases:	I sec (modeled as white noise)
Eight Ground Locations:	1 km each component
Zenith Atmospheric Delays:	SO cm (modeled as random walk)

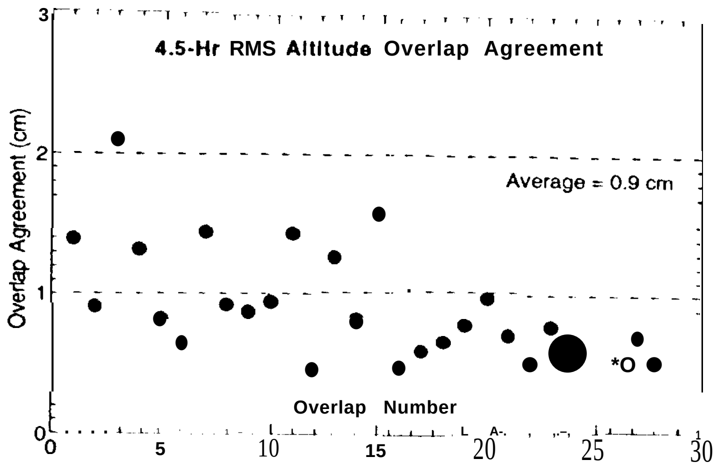


Fig. 5. RMS agreement on 4.5-hr orbit overlaps for reduced dynamic solution for all 28 overlaps of the 29-day set.

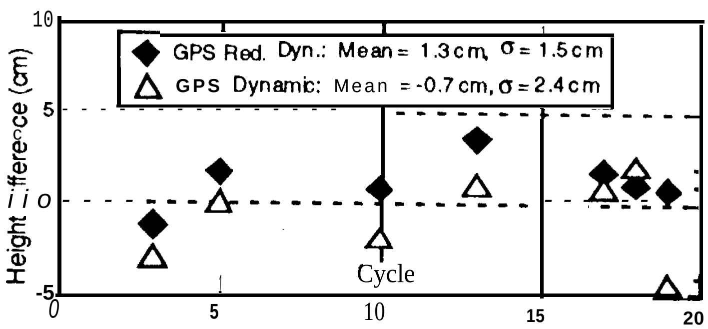
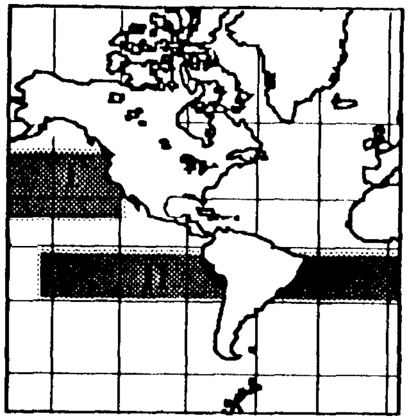


Fig. 6. GPS dynamic and reduced dynamic TOPEX/Poseidon heights difference with short arc laser height measurement over Harvest platform.



RMS Crossover
D inferences (cm)

Region	GSFC Dyn. *	GPS R. D.
Global	10.31	9.86
Region I	8,10	7.99
Region 11	8.43	7.65

*laser & DORIS data

Fig. 7. Summary of RMS altimetry crossover differences with laser/DORIS dynamic orbit solutions and GPS reduced dynamic solutions,

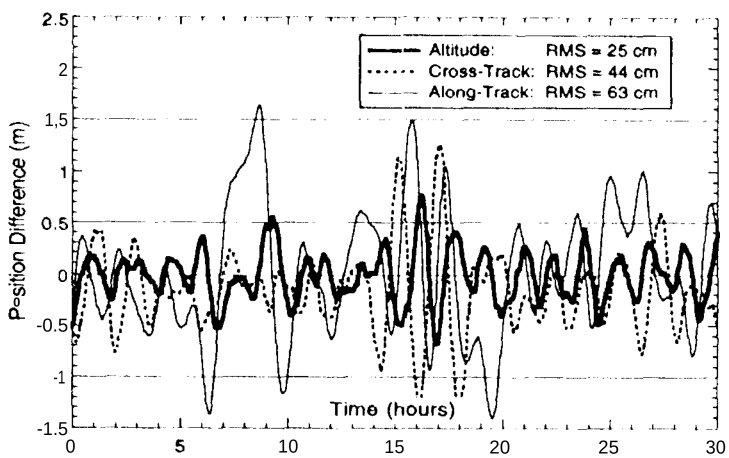


Fig. 8. Difference between dynamic solution with GEM-T 1 gravity model and reduced dynamic solution with the tuned JGM-2 model.

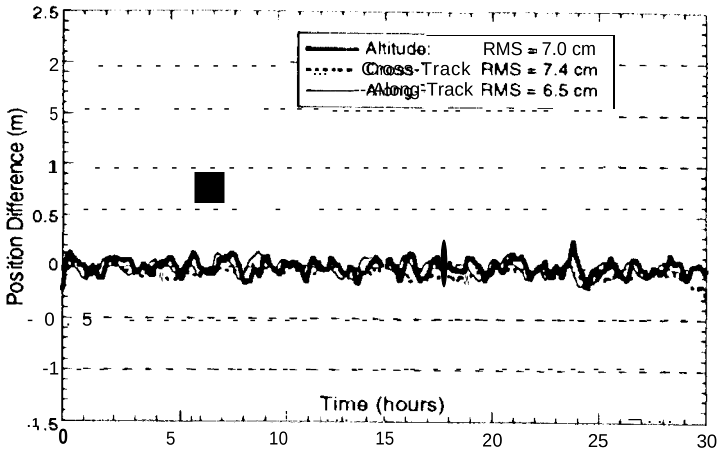


Fig. 9. Difference between reduced dynamic solutions with the GEM-T1 andJGM-2 gravity models,